ARCTIC
VOL. 36, NO. 3 (SEPTEMBER 1983) P. 251-261

Distribution of Hydrocarbons and Microbial Populations Related to Sedimentation Processes in Lower Cook Inlet and Norton Sound, Alaska[1,2,3]

RONALD M. ATLAS[4], MAHALAKSHMI I. VENKATESAN[5], ISAAC R. KAPLAN[5], RICHARD A. FEELY[6], ROBERT P. GRIFFITHS[7] and RICHARD Y. MORITA[7]

ABSTRACT. In spring and summer 1978 and spring 1979 an integrated study was carried out to examine the interrelationships of physical (sediment deposition), chemical (organic carbon and hydrocarbon concentrations), and biological (microbial populations and activities) factors in the Cook Inlet and Norton Sound regions with respect to the probable sinks and fates of hydrocarbon contaminants within these ecosystems. Most of the fine-grained sediment entering Cook Inlet is transported out of the inlet into Shelikof Strait; however, significant sediment accumulation occurs within areas of Kamishak and Kachemak bays. In Norton Sound, sediment from the Yukon River is transported counterclockwise around the embayment and approximately 50% is deposited in the nearshore regions of the sound. In both regions, areas of high sediment accumulation are richer in organic carbon and hydrocarbon derived from land than are areas of low sediment accumulation. In general, areas with high sediment accumulation rates for fine-grained particles are also areas of relatively high microbial activity. Results suggest that these elevated microbial activities reflect biodegradation of detrital carbon associated with these particles. Also, the Cook Inlet and Norton Sound region were found to be free from petroleum hydrocarbon contamination (with the exception of one area in Cook Inlet). No evidence was found of hydrocarbon accumulation resulting from a gas seepage in Norton Sound, nor for accumulation of hydrocarbons in sediments of lower Cook Inlet and Shelikof Strait from oil well operations in upper Cook Inlet.

Key words: arctic marine ecosystems, sedimentation, microorganisms, hydrocarbons, lower Cook Inlet, Norton Sound

RESUME. Une étude intégrée a été effectuée lors du printemps et de l'été de 1978 et du printemps de 1979 en vue d'examiner les corrélations des facteurs physiques (dépôt de sédiments), chimiques (concentrations de carbone et d'hydrocarbures organiques) et biologiques (population et activités microbiennes) dans les régions de l'inlet Cook et du bras de mer Norton quant aux résultats probables de la contamination de ces écosystèmes par les hydrocarbures. La majeure partie des sédiments à grains fins entrant dans l'inlet Cook sont transportés de l'inlet dans le détroit Shelikof. Cependant, il se produit une accumulation significative de sédiments dans les régions des baies Kamishak et Kachemak. Dans les bras de mer Norton, les sédiments provenant du fleuve Yukon sont transportés dans le sens contraire des aiguilles d'une montre autour de la baie et environ 50% sont déposés près du littoral du bras de mer. Dans ces deux régions, les endroits présentant une accumulation importante de sédiments sont plus riches en carbones et hydrocarbures organiques provenant de la terre que le sont les endroits ayant peu d'accumulation de sédiments. En général, les régions ayant un taux élevé d'accumulation de sédiments fins témoignent aussi d'une activité microbienne relativement élevée. Les résultats suggèrent que cette augmentation en activitè microbienne reflète la biodégradation du carbone détritique associé à ces particules. De plus, les régions de l'inlet Cook et du bras de mer Norton ne présentaient aucune contamination d'hydrocarbures de pétrole, sauf à un endroit dans l'inlet Cook. Aucune accumulation d'hydrocarbures ne peut être attribuée à des indices de gaz dans le bras de mer Norton et aucune accumulation d'hydrocarbures dans les sédiments dans le sud de l'inlet Cook et le détroit Shelikof ne résultaient de l'exploitation pétrolifère en cours dans le nord de l'inlet Cook.

Mots clés: écosystèmes marins arctiques, sédimentation, micro-organismes, hydrocarbures, sud de l'inlet Cook, bras de mer Norton

Traduit pour le journal par Maurice Guilbord.

INTRODUCTION

Both the Norton Sound and Cook Inlet regions of Alaska are potential sites of future offshore oil and gas development. Examination of existing levels of hydrocarbons, sedimentation processes, and microbial populations permits an assessment of the likely sinks and fates of crude oil that may enter these ecosystems as a result of petroleum development. Hydrocarbon contaminants may become associated with suspended sediment and become concentrated in areas of active sediment accumulation. It is in such benthic regions, where the impact of contaminants on ecological processes may be the greatest, that microbial degradation of hydrocarbons in surface sediments can be a significant decontamination process which can potentially mitigate the impact of oil contamination.

At the same time of this study, both the Cook Inlet and Norton Sound regions were thought to receive hydrocarbon contaminants. It was hypothesized that hydrocarbons released as a result of normal operations of offshore oil wells in upper Cook Inlet might accumulate within the sediments of lower Cook Inlet. A reported gas seepage in Norton Sound (Cline and Holmes, 1977) was considered to be a potential source of contaminating hydrocarbons that could be traced in the sediment of that region.

MATERIALS AND METHODS

Study Region

Cook Inlet is a large tidal estuary in south Alaska (Fig. 1). Physiographically, Cook Inlet is divided into three sections: the head region, which is further divided into the Knik Arm and the Turnagain Arm; upper Cook Inlet; and lower Cook Inlet. Upper Cook Inlet is separated from lower Cook Inlet just

[1]Published as Technical Paper No. 6556, Oregon Agricultural Experiment Station.
[2]Contribution no. 2303, Institute of Geophysics and Planetary Physics, University of California, Los Angeles.
[3]Contribution no. 542 from the Pacific Marine Environmental Laboratory, NOAA.
[4]Department of Biology, University of Louisville, Louisville, Kentucky 40292, U.S.A.
[5]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, California 90024, U.S.A.
[6]Pacific Marine Environmental Laboratory, National Oceanographic and Atmospheric Administration, Building 32, 7600 Sand Point Way N.E., Seattle, Washington 98115, U.S.A.
[7]Department of Microbiology and School of Oceanography, Oregon State University, Corvallis, Oregon 97331, U.S.A.

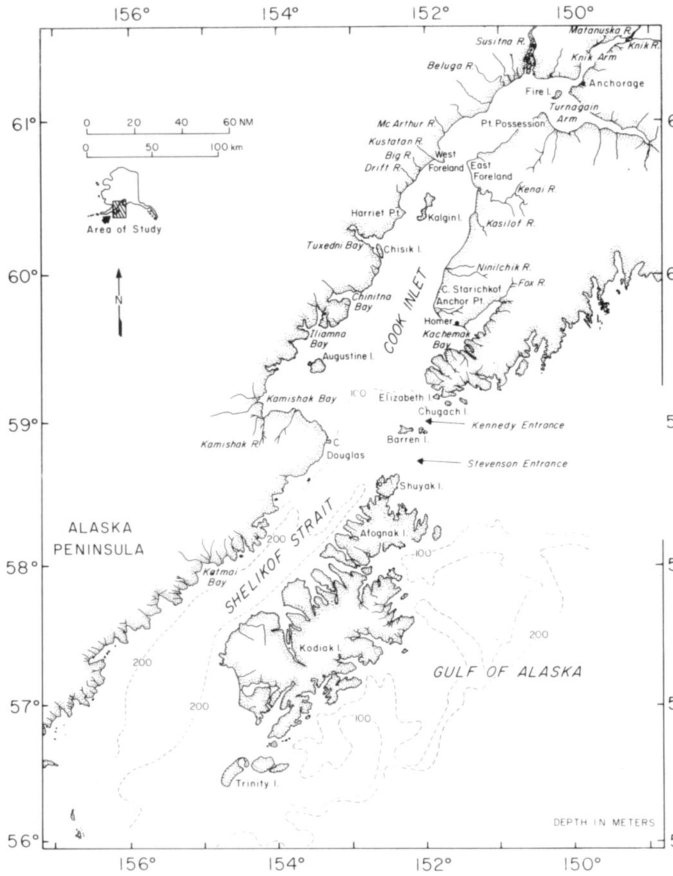

FIG. 1. Chart of Cook Inlet region showing depth in metres.

north of Kalgan Island by the East and West Forelands. The coastline of lower Cook Inlet is characterized by several small embayments and two large embayments: Kamishak Bay and Kachemak Bay. At its mouth, the inlet opens into the Gulf of Alaska to the southeast, and into Shelikof Strait to the southwest. Shelikof Strait is separated from the Gulf of Alaska by several islands, including Afognak and Kodiak islands.

Upper Cook Inlet receives freshwater and suspended sediment from the Matanuska and Knik rivers at the head of the Knik Arm and the Susitna and Beluga rivers to the northwest. The combined flow of these rivers supplies ~70-80% of the freshwater input and 75-90% of the total suspended sediment input to upper cook Inlet (Rosenberg and Hood, 1967). Suspended sediment in these rivers is derived from glacial erosion at higher elevations. In addition to the discharge of rivers flowing into upper Cook Inlet, the lower inlet receives suspended sediment from several smaller rivers that carry glacial flour into the inlet from both sides.

The distribution and composition of bottom sediments in Cook Inlet has been reported (Bouma and Hampton, 1976; Hein *et al.*, 1979). The sediments are composed primarily of medium- to fine-grained sands; however, silt- and clay-sized sediments have been observed within the embayments. The deposits in the northern part of the inlet are winnowed Pleistocene-early Holocene gravels, and many sand-sized and smaller particles have been removed and redeposited in the south. In addition to relict sands and gravels, the bottom deposit also contains some modern fine-grained silts and clays.

Water circulation in the inlet is characterized by a net inward movement of oceanic water up the eastern shore and a net outward movement of a mixture of oceanic water and runoff water along the western shore (Muench *et al.*, 1978). In the vicinity of the Forelands, the water masses are vertically mixed due to the turbulent action of tidal currents.

Norton Sound is a shallow embayment of the Bering Sea in the central region of the west coast of Alaska (Fig. 2). The Yukon River, which flows into the southwest quadrant of the embayment, is the primary source of freshwater and suspended matter to the sound as well as to the entire eastern Bering Sea shelf. Its annual load of suspended matter, 88×10^6 tons, ranks 18th among the major rivers of the world (Inman and Nordstrom, 1971). The distribution of sediments in Norton Sound has been summarized by Sharma (1974), Nelson and Creager (1977), and McManus *et al.* (1977).

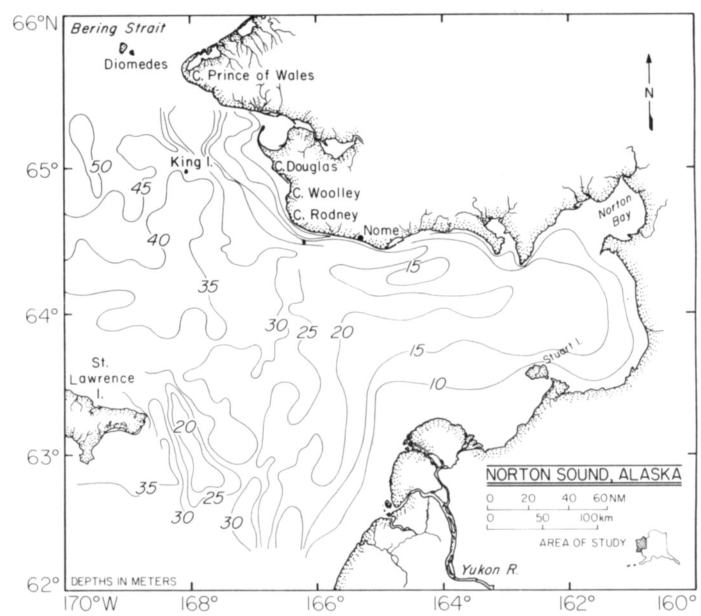

FIG. 2. Chart of Norton Sound region showing depth in metres.

The shelf water west of Norton Sound, the Alaskan coastal water, has a net northward flow of about 1.5×10^6 $m^3 \cdot sec^{-1}$ (Muench *et al.*, 1981). About one-third of this flow passes between St. Lawrence Island and the mouth of Norton Sound and induces a counterclockwise water circulation within Norton Sound. The intensity of the counterclockwise flow appears to be affected by local winds and by freshwater runoff. The eastern half of the sound is characterized by two vertically well-mixed layers. The upper layer contains runoff water from the coastal rivers; the lower layer contains cold, dense residual water formed during the previous winter. Both water masses follow the general pattern of counterclockwise flow in the region, though much more sluggishly than surface and bottom water further to the west (Coachman *et al.*, 1975; Muench and Ahlnäs, 1976; Muench *et al.*, 1981).

Sample Collection

Sediment samples were collected within Cook Inlet during

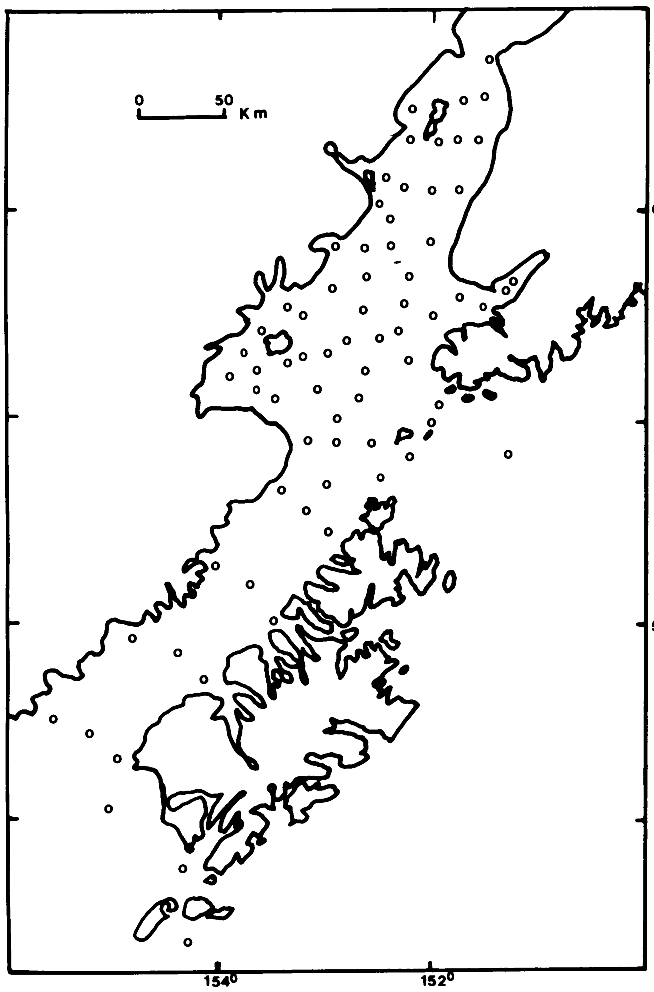

FIG. 3. Chart showing sampling site locations in lower Cook Inlet.

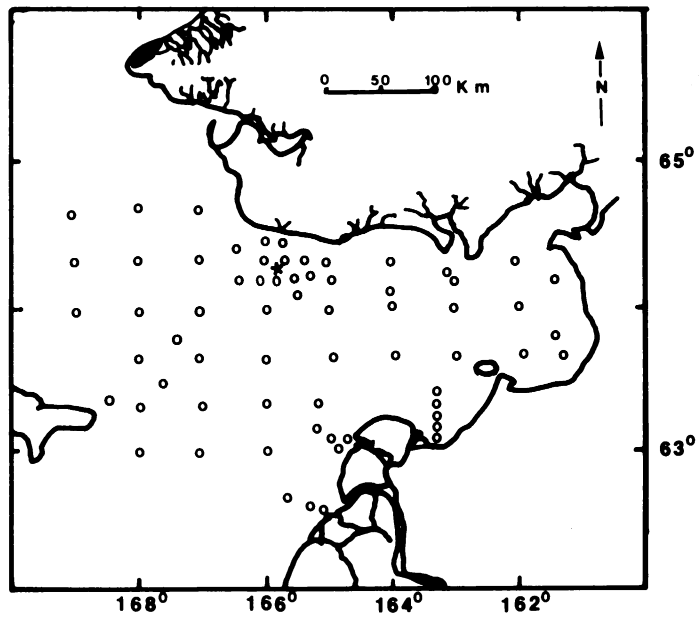

FIG. 4. Chart showing sampling site locations in Norton Sound. * indicates location of reported gas seepage.

spring 1978, summer 1978, and spring 1979. Samples were collected from stations located throughout lower Cook Inlet and Shelikof Strait, including Kamishak Bay (western lower Cook Inlet) and Kachemak Bay (eastern lower Cook Inlet). The locations of the general grid of stations used for sampling are shown in Figure 3; however, not all stations were sampled for all parameters and some data were supplemented with additional samples to obtain greater resolution. (For details of the exact sampling locations for each parameter see Feely *et al.*, 1981; Kaplan *et al.*, 1980; Haines *et al.*, 1981.) A plastic-lined gravity corer, three inches in diameter, was used to collect 25 samples for the studies of sediment accumulation rate in Cook Inlet and Shelikof Strait. Sediment was collected at 50 stations in the Norton Sound region during July 1979 (Fig. 4). For the chemical and microbiological analyses, samples were collected with a frame-supported Van Veen grab sampler; the upper 2 cm of the recovered sediment was used for analyses.

Rates of Fine-Grained (< 62μm) Sediment Accumulation

Two procedures were used to produce maps of the rates of accumulation of fine-grained sediment in Cook Inlet and Norton Sound. For the Cook Inlet data, sediment cores were cut into 2-cm sections, placed in polyethylene bags, and frozen. The frozen sections were sent to C.W. Holmes and C.A. Martin (U.S. Geological Survey, Corpus Christi, Texas) for ^{210}Pb geochronological studies following the methods described by Flynn (1968). These analyses provide a detailed picture of recent (for approximately the past 100 years) sedimentation history and are based on the deposition of ^{210}Pb, formed from ^{222}Rn in the atmosphere, in surface fine-grained sediments. The half life of ^{210}Pb is 22 years and its vertical distribution in buried sediments is a function of the rate of sediment deposition and mixing (Nittrouer *et al.*, 1979). The relative abundance of ^{210}Pb can be used to date the sediment and to estimate the rate of sediment accumulation. For the Norton Sound data, sediment accumulation maps were redrafted from the accumulation rates derived from the geophysical data provided by Nelson and Creager (1977). The estimated age and thickness of Norton Sound sediments were based on geophysical records and estimated time of shoreline transgression, based on independently dated peat and wood layers within the sediments. These data provided a record spanning approximately the past 12 000 years. Both sets of data are presented in units of $g \cdot cm^{-2} \cdot yr^{-1}$.

Organic Carbon Analyses

Inorganic carbonates were removed by successive treatment with 1 N and 6 N HC1. The sediments were washed with deionized water to a pH of ca. 7.0 and centrifuged. The sediment samples were then combusted in a LECO carbon analyzer to convert the organic carbon to CO_2 which was measured with a thermal conductivity detector.

Hydrocarbon Analyses

Frozen sediment samples were thawed and extracted with methanol for 24 hr and then with toluene:methanol for 76 hr. The extracts were processed following the methodology of Venkatesan *et al.* (1981) and separated into aliphatic and aromatic fractions by silica-gel-column chromatography using hexane and hexane:benzene (3:2 v/v) respectively.

The aliphatic and aromatic fractions were analyzed using a Hewlett-Packard Model 5830A gas-liquid chromatograph, modified with a Grob injector and equipped with flame ionization detector and electronic integrator. The glass capillary column (30 m × 0.25 mm), OV-101 (J and W, Inc.) was temperature programmed at 4° C/min from 35° C to 260° C and held isothermally for about 2 hr.

Enumeration of Microorganisms

Enumeration of total bacterial populations was performed using a direct count procedure. Samples were preserved with one part formaldehyde:one part sample (v/v). Samples were filtered through 0.2-μm cellulose nitrate black filters and stained with acridine orange according to the procedure of Daley and Hobbie (1975). Samples were viewed with an Olympus epifluorescence microscope with a BG-12 exciter filter and 0-530 barrier filter. Ten fields per filter and two filters per sample were viewed and the counts averaged.

A Most Probable Number (MPN) procedure was used to estimate numbes of hydrocarbon-utilizing microorganisms (Atlas, 1979). Dilutions of samples were added to 30-ml, stoppered serum vials containing 5 ml of autoclaved Bushnell Haas broth (Difco) with 3% added NaCl, and 50μl filter sterilized (0.2 μm Millipore filtered) Cook Inlet crude oil spiked with 1-^{14}C*n* hexadecane (s.p. act. - 0.9 μCi/ml oil). A 3-tube MPN procedure was used. Following incubation at 5° C for four weeks the $^{14}CO_2$ produced from microbial hydrocarbon degradation was recovered by purging the vials with air and trapping the $^{14}CO_2$ in 10 ml Oxifluor CO_2 (New England Nuclear). Counting was done with a Beckman liquid scintillation counter. The numbers of positive ($^{14}CO_2$-producing) and negative vials were recovered and the most probable number of hydrocarbon-degrading microorganisms was determined from the appropriate MPN Tables.

Relative Microbial Activities

Relative microbial activities were measured using the single substrate concentration method described by Griffiths *et al.* (1977). Ten-ml subsamples of sediment slurry, prepared by diluting a known weight of sediment with sterile seawater ($\cong$1:1000) were placed into 50-ml serum bottles. We added either uniformly labelled ^{14}C glucose, sp. act. $\cong$300 m Ci/m M, to give a final concentration of about 4μg·l^{-1}, or uniformly labelled ^{14}C glutamate, sp. act. = 10 m Ci·ml^{-1}, to yield a final concentration of about 150 μg·l^{-1}. The bottles were sealed with rubber serum caps fitted with plastic rod and cup assemblies (Kontes Glass Co.) containing 25 × 50-mm strips of fluted filter paper. All determinations were run in triplicate. The samples were incubated in the dark within 0.5° C of the *in situ* temperature. The $^{14}CO_2$ was adsorbent and was trapped using β-phenethylamine which was injected onto the filter paper. The filter papers containing the $^{14}CO_2$ were removed from the cup assemblies and added to scintillation vials containing 10 ml of toluene-based scintillation fluor (Omnifluor, New England Nuclear). Subsamples then were filtered through a 0.45-μm membrane filter (Millipore). The trapped cells on the filters were dried and added to scintillation vials containing 10 ml of scintillation fluor. All vials were counted in a Beckman model LS-100 liquid scintillation counter. For calculating percent respiration, the number of radioactive counts released as CO_2 was divided by the counts incorporated into the cells plus the counts respired as $^{14}CO_2$.

Acute Effects of Hydrocarbons on Relative Microbial Activity

The assay for relative microbial activity was conducted as above, except that 10 μl of Cook Inlet crude oil were added to the reaction mixture. The relative microbial activity was assayed by withdrawing 5 ml of sediment dilution from underneath the surface slick with a syringe fitted with a stainless-steel needle. The cells were washed and trapped as usual, and the resulting counts were doubled to account for the reduced volume. Activities with oil added were compared to those measured in the absence of oil to determine the percent inhibition.

RESULTS

Sediment Accumulation

The regions of sediment accumulation within lower Cook Inlet which were studied include, in decreasing order of importance, Shelikof Strait, Kamishak Bay, and Kachemak Bay (Fig. 5). Unfortunately, rates of sediment accumulation could not be determined for the central area of Cook Inlet because no cores were successfully collected there. However, the central basin of Cook Inlet is largely composed of relict sands and gravel (Bouma and Hampton, 1976; Hein *et al.*, 1979), and it

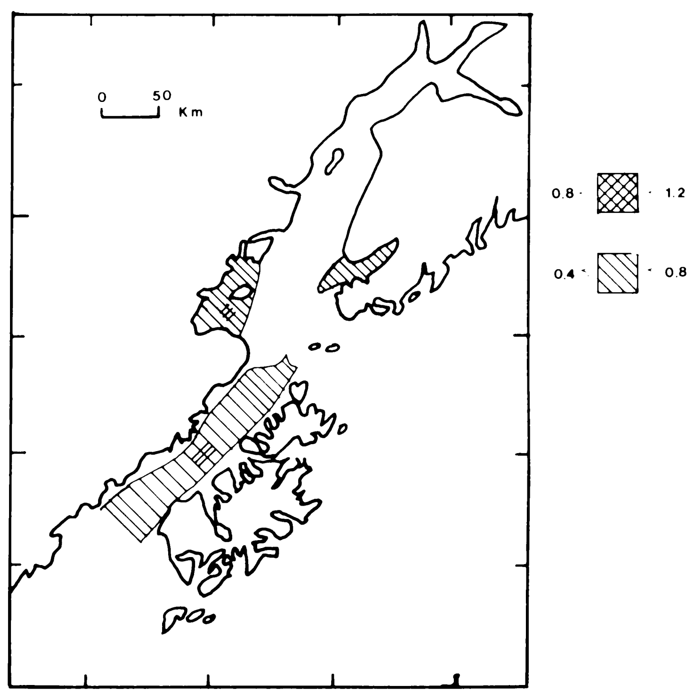

FIG. 5. **Rates of sediment accumulation in lower Cook Inlet (g·cm^{-2}·yr^{-1}). While there are no data available for the central part of lower Cook Inlet, the grain-size data of Bama and Hein (1971) indicate little or no fine-grained sediment in that region.**

therefore does not appear to be a site for accumulation of fine-grained sediment. Integrating the measured rates of sediment accumulation over the areas for Kamishak Bay and Kachemak Bay yield estimates of 4.9×10^{12} g·y^{-1} and 2.3×10^{11} g·y^{-1}, respectively. This represents only about 18% of the total annual input of suspended sediments to Cook Inlet from rivers, which is estimated to be approximately 2.8×10^{13} g·y^{-1} (Gatto, 1976; Sharma, 1979).

It appears that most of the fine-grained sediments entering Cook Inlet are transported out of the inlet and are deposited within Shelikof Strait to the west of Kodiak Island. Rates of sediment accumulation within Shelikof Strait are estimated to be about 6.2×10^{13} g·y^{-1}, or 220% of the annual amount of suspended sediments entering Cook Inlet. Detailed chemical and grain size analyses indicate that the suspended sediments in Shelikof Strait consist of clay-sized suspended material from Cook Inlet (Massoth *et al.*, 1979), terrigenous sediments from the Copper River in the northeast Gulf of Alaska (Feely and Massoth, 1982), and biogenic material produced in the water column (Feely and Massoth, 1982). If these materials form the bulk of fine-grained sediments in Shelikof Strait, then the data indicate that the sediments of Shelikof Strait are composed of a mixture of Cook Inlet and Copper River-derived material. This conclusion is supported by the clay mineral data of Hein *et al.*, (1979) which indicate that the fine-grained sediments in Shelikof Strait primarily consist of a chlorite-rich suite from the Copper River and an illite-rich suite from the Susitna River.

Within the Norton Sound region, the highest rates of sediment accumulation were found to be around the Yukon River delta (Fig. 6). There appears to be a counterclockwise transfer of suspended sediment through Norton Sound but no major region of sediment accumulation equivalent to the Shelikof Strait region was found in or near Norton Sound. Tidal and storm currents within Norton Sound appear to resuspend and redistribute sediment within the sound itself (Nelson and Creager, 1977).

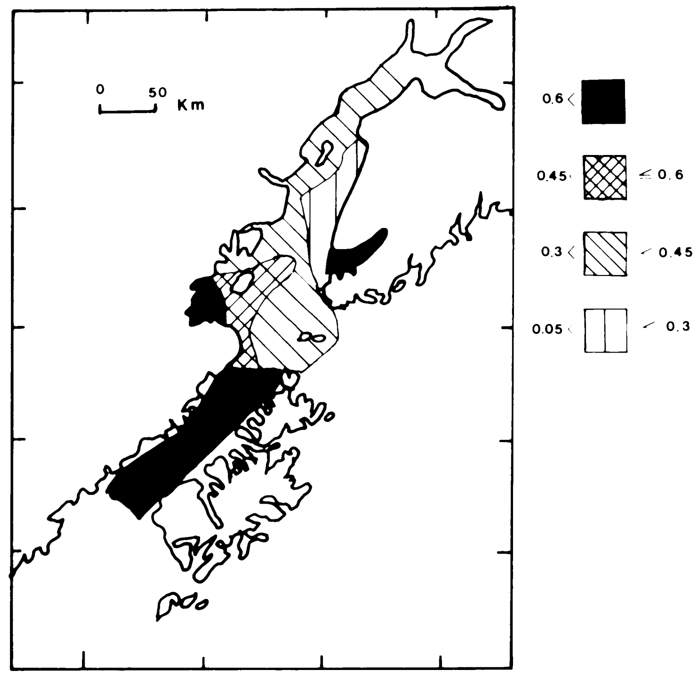

FIG. 7. Percent organic carbon in sediments of Cook Inlet.

Organic Carbon

The highest total organic carbon concentrations are in Kachemak Bay, Kamishak Bay, and Shelikof Strait (Fig. 7). The range of organic carbon content in or near Cook Inlet is from 0.06 to 1.30%. A similar range of organic carbon concentrations (0.12-1.30%) was found in Norton Sound. The distribution of organic carbon generally was highest near the shore; it was lower northwest of Norton Sound and in the Yukon River delta (Fig. 8). Sediments in the open ocean have a slightly lower carbon content in general than those near shore in the Yukon delta. The lower organic carbon content in this region most probably reflects its distance from the Yukon River, which is the major source of terrestrial sediments (Venkatesan *et al.*, 1981).

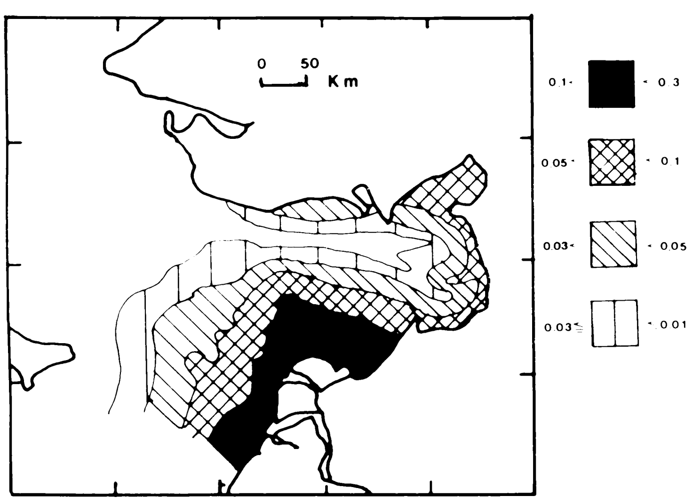

FIG. 6. Rates of sediment accumulation in Norton Sound (g·cm^{-2}·yr^{-1}; modified after Nelson and Creager, 1977).

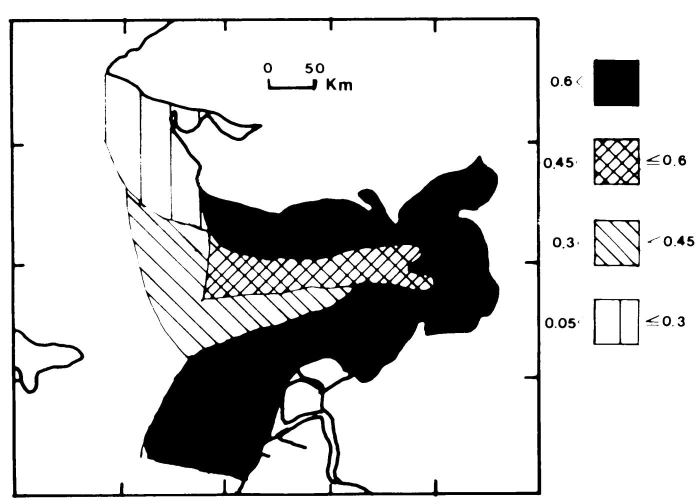

FIG. 8. Percent organic carbon in sediments of Norton Sound.

Hydrocarbons

The analyses of Cook Inlet samples indicate that the hydrocarbon concentrations (nonsaponifiable lipid fraction) are highest in Kachemak Bay and lowest in the central and upper parts of lower Cook Inlet (Fig. 9). The upper Shelikof Strait region shows areas of high lipid concentrations. The Kamishak Bay region shows moderate lipid concentrations. In general, the concentrations of resolved *n*-alkanes follow the same trends. Samples from Kachemak Bay and Kamishak Bay generally contained hydrocarbons with odd/even *n*-alkane ratios of greater than 3.0, which indicates terrigenous inputs (Kollatukudy and Walton, 1972). Lower odd/even *n*-alkane ratios were found in the central part of lower Cook Inlet, indicating less terrigenous input. However, a bimodal distribution of alkanes from sediments in the entire area suggests a mixed marine and terrestrial origin of the lipids (Kaplan *et al.*, 1980). Most of the chromatograms lack an unresolved envelope, indicating that the hydrocarbons were not of petroleum origin. One exception appears in data from upper Cook Inlet, just north of Kalgin Island, where measurements show an area of relatively high localized concentrations of hydrocarbons and the gas chromatograms had an unresolved envelope with an odd/even *n*-alkane ratio of approximately 1.0, indicating evidence for petroleum hydrocarbon inputs. The distribution of polynuclear aromatic (PAH) compounds within Cook Inlet sediments generally shows a pattern of parent PAH $>$ C_1 substituted PAH $>$ C_2 substituted PAH $>$ C_3 substituted PAH concentrations, further indicating a general absence of petroleum inputs.

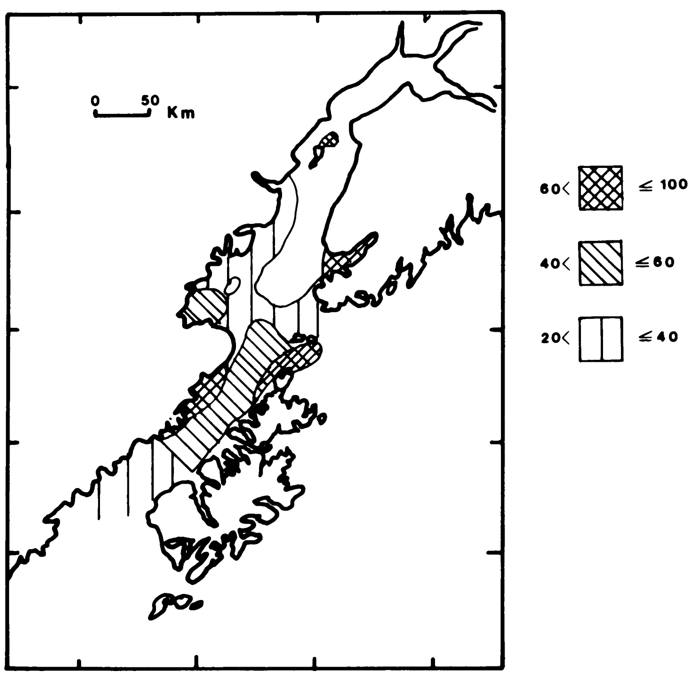

FIG. 9. Concentration of nonsaponifiable lipid fraction in Cook Inlet ($\mu g \cdot g^{-1}$).

Generally, higher concentrations of lipids were found in Norton Sound sediments than in Cook Inlet sediments (Fig. 10). The highest lipid concentrations in Norton Sound occurred near the shore east of the Yukon River delta. Lipid concentrations were lower in the northern half of Norton Sound than along the southern and eastern shores. Lower hydrocarbon concentrations were generally found outside Norton Sound than in the sound proper, probably because the terrigenous detritus outside Norton Sound is diluted by ocean sedimentation (Venkatesan *et al.*, 1981). Hydrocarbon concentrations were not elevated in the vicinity of the reported gas seepage (Cline and Holmes, 1977) south of Nome (≅ 64°N, 165°W) and the sediments did not show *n*-alkanes or triterpenoidal distributions characteristic of petroleum. There was a predominance of odd-numbered *n*-alkanes from C_{23} to C_{31} with a maximum at nC_{27}, which is indicative of land-derived plants (Kollatukudy and Walton, 1972). Hydrocarbons from marine plankton were very low within Norton Sound compared to stations outside of the sound. Unsubstituted parent polynuclear aromatic hydrocarbons predominated over C_1-C_3 substituted PAH compounds.

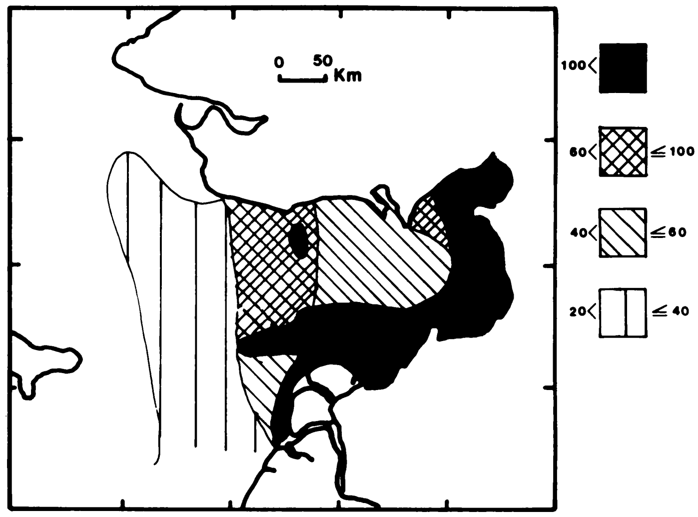

FIG. 10. Concentration of nonsaponifiable lipid fraction in Cook Inlet ($\mu g \cdot g^{-1}$).

Microbial Populations

Total numbers of microorganisms were about an order of magnitude lower in the northern and central portions of lower Cook Inlet than elsewhere in the lower Cook Inlet region (Fig. 11). The greatest microbial biomass was found just southeast of the entrance to Cook Inlet. Within Norton Sound, along a northwesterly path from the mouth of the Yukon River, concentrations of microbial biomass were found to be lower than elsewhere in the sound (Fig. 12). The highest numbers of microorganisms were found near the reported Norton Sound gas seepage. In both Norton Sound and lower Cook Inlet and Shelikof Strait the range of total numbers of microorganisms was similar, generally with a variation of only one order of magnitude.

Numbers of hydrocarbon utilizers within Cook Inlet were much more variable than were numbers of total microorganisms (Fig. 13). Relatively higher concentrations of hydrocarbon utilizers were found within nearshore regions than within the central portions of the inlet. High concentrations of hydrocarbon utilizers also were found at the upper end

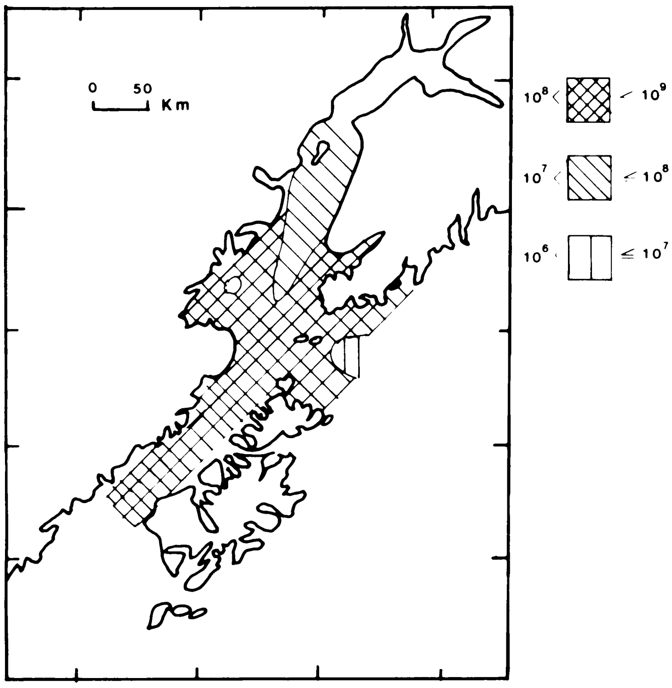

FIG. 11. Direct counts of total microorganisms in Cook Inlet ($\#\cdot g^{-1}$).

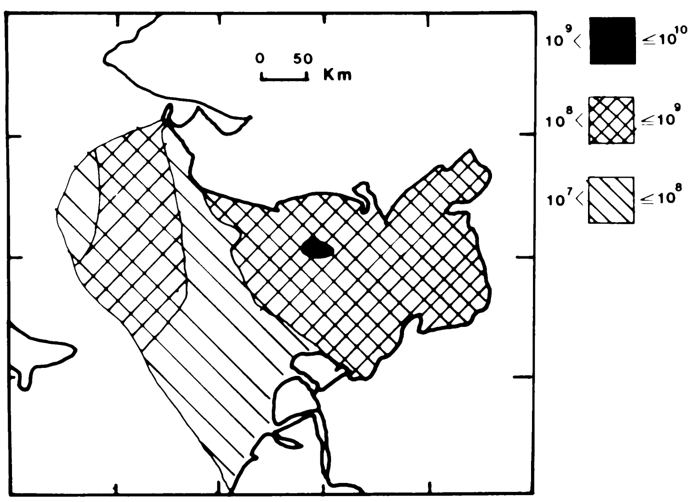

FIG. 12. Direct counts of total microorganisms in Norton Sound ($\#\cdot g^{-1}$).

of Shelikof Strait and just southeast of the entrance to Cook Inlet. The largest determined number of hydrocarbon utilizers occurred in the northern portion of Kamishak Bay in a region known as Oil Bay.

Northwest from the mouth of the Yukon River the numbers of measured hydrocarbon utilizers are low (Fig. 14). There is a localized area of high numbers of hydrocarbon utilizers near the southwest outlet of the Yukon River and a more extensive area of relatively high numbers of hydocarbon utilizers at the southeast inner end of the sound. No elevated numbers of hydrocarbon utilizers, above the background numbers characteristic of the region, were found near the site of the Norton Sound gas seepage.

Microbial Activities

The highest rates of microbial activity were measured along the western shores of upper Cook Inlet in the vicinity of Tuxedni Bay (Fig. 15). Relatively high rates of microbial activity also were found in sediments of Kachemak and Kamishak bays. Low rates of microbial activity were found in Shelikof Strait sediments. The average rates of glucose and glutamate uptake within Cook Inlet, excluding Shelikof Strait, were 6 and 162 $ng\cdot g^{-1}\cdot h^{-1}$, respectively. The average percentages of the substrates respired were 24 and 45 for glucose and glutamate, respectively.

The mean rates of glucose and glutamate uptake within Norton Sound were 28 and 127 $ng\cdot g^{-1}\cdot h^{-1}$, respectively. Thus, the mean rate of glucose uptake was 4.5 times higher within Norton Sound than within Cook Inlet. Rates of glutamate utilization, though, were slightly lower in Norton Sound than

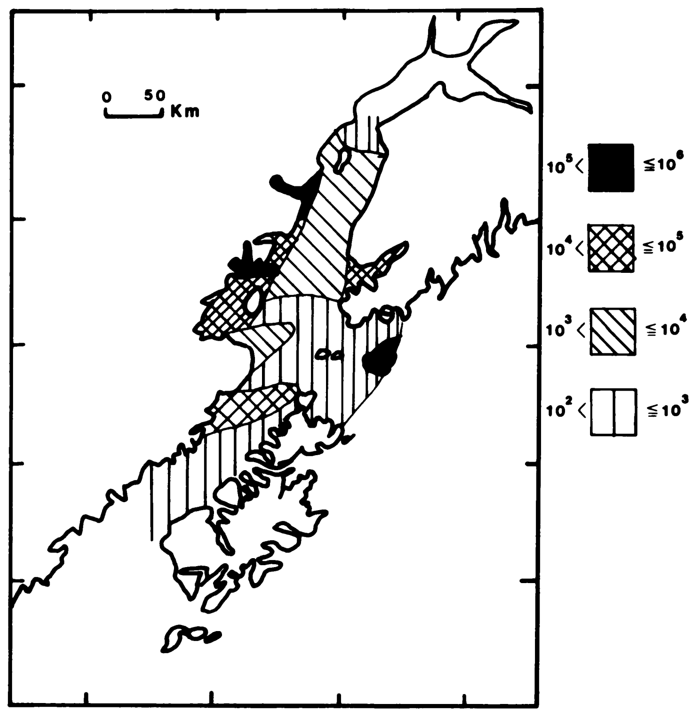

FIG. 13. Most Probable Numbers of hydrocarbon utilizers in Cook Inlet ($\#\cdot g^{-1}$).

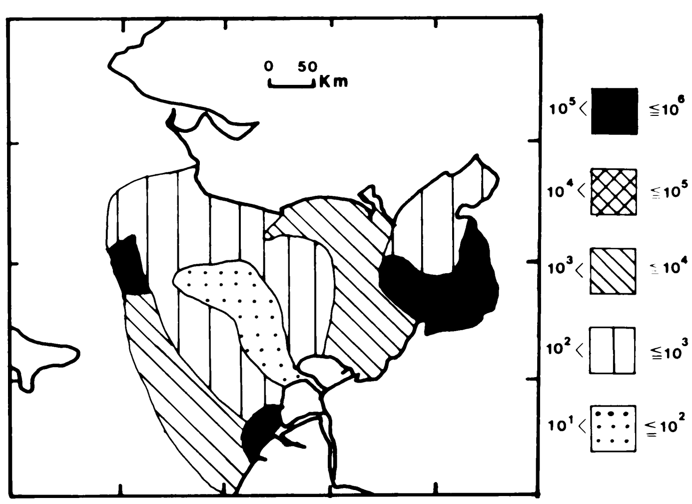

FIG. 14. Most Probable Numbers of hydrocarbon utilizers in Norton Sound ($\#\cdot g^{-1}$).

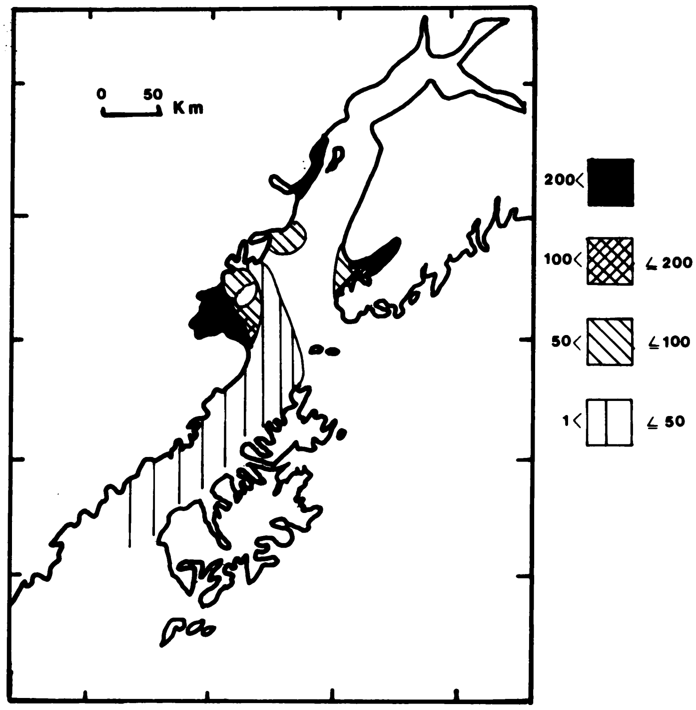

FIG. 15. Relative microbial activities (V_{max}) for glutamate uptake in Cook Inlet ($ng \cdot g^{-1} \cdot h^{-1}$).

within Cook Inlet. Relatively high rates of microbial activity were found at the innermost portion of Norton Sound (Fig. 16). The level of microbial activity was low, however, in waters along a northwesterly track from the mouth of the Yukon River.

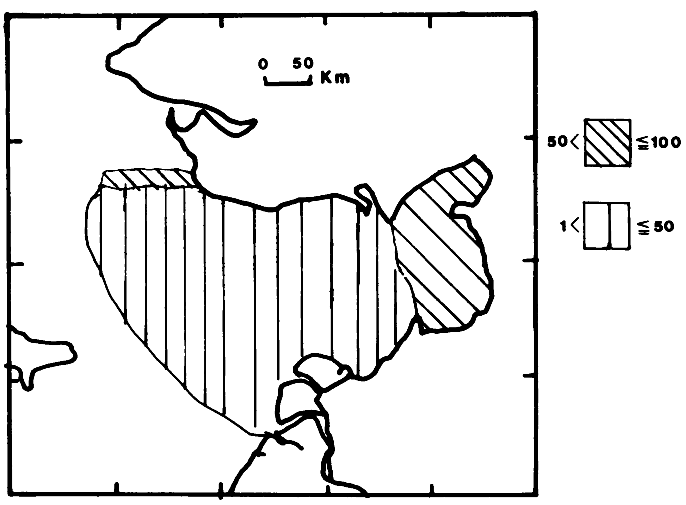

FIG. 16. Relative microbial activities (V_{max}) for glucose uptake in Norton Sound ($ng \cdot g^{-1} \cdot h^{-1}$).

Effects of Hydrocarbons on Microbial Activities

The degree to which exposure to petroleum hydrocarbons inhibits rates of glucose uptake by microbial populations varies greatly in sediments of both Cook Inlet and Norton Sound. A high degree of inhibition was observed within Kamishak Bay, but only limited inhibition was observed within Tuxedni Bay and at the tip of Shelikof Strait in the Cook Inlet region. The degree of inhibition was very low (0-12%) in some water samples collected near Kalgin Island and Oil Bay, but within the water column of these areas the apparent adaptation of bacterial populations to hydrocarbon exposure was not shown by the underlying benthic bacterial community. Within Norton Sound a relatively high degree of inhibition was found northwest of the Yukon delta, and relatively little inhibition was found in the southeastern portion of the sound, as well as in several central regions of the sound. There was no evidence of adaptation to hydrocarbons in the vicinity of the gas seepage.

DISCUSSION

Cook Inlet

The results of this study, together with the work of previous investigators (Bouma and Hampton, 1976; Hein *et al.*, 1979; Feely *et al.*, 1981), indicate that most of the suspended material discharged from local rivers into Cook Inlet is deposited in Shelikof Strait and not within the inlet proper. The Kachemak Bay and Kamishak Bay areas are sites of additional significant sediment accumulation, but it is of lesser magnitude than in Shelikof Strait. These findings suggests that petroleum hydrocarbons which are released within Cook Inlet and which become associated with fine-grained suspended sediment will accumulate primarily in Shelikof Strait, with secondary accumulations in Kachemak and Kamishak bays.

At the time of this study there was no evidence for petroleum hydrocarbon accumulation in sediments of lower Cook Inlet or Shelikof Strait resulting from offshore oil well operations in upper Cook Inlet. The alkanes in sediments of the study area generally showed a bimodal distribution of biogenic origin typical of a mixture of marine and terrestrial hydrocarbons. The odd carbon predominance of *n*-alkanes characteristic of terrestrial plants was evident particularly in areas of sediment accumulation. A complex mixture of polynuclear aromatic hydrocarbons was identified by GC/MS in all the sediments. The relative distribution of parent homologs and their alkylated derivatives is characteristic of natural and/or anthropogenic pyrolytic sources rather than of crude oil.

The only site of petroleum hydrocarbon contamination of benthic sediments was found in upper Cook Inlet just north of Kalgin Island. Numbers of hydrocarbon-utilizing microorganisms in the coarse sediments of upper Cook Inlet were not high even in the area of possible petroleum-contaminated sediment. Especially high numbers of hydrocarbon-utilizing microorganisms were found in the water column just north of Kalgin Island, immediately overlying the area where petroleum-derived hydrocarbons were detected in the sediments (Roubal and Atlas, 1978). The microorganisms in some water samples collected in the vicinity of Kalgin Island were particularly tolerant of exposure to petroleum hydrocarbons, showing only a 0-12% reduction in the rates of glucose uptake compared to a 40-50% reduction in most water samples collected elsewhere within Cook Inlet. There was no evidence for adaptation to hydrocarbon exposure (i.e. tolerance to petroleum hydrocarbons by microorganisms) within sediments

TABLE 1. Interparameter correlation coefficient matrix for the lower Cook Inlet Data Set[1]

	Organic Carbon	Sediment Accumulation	Total Lipids	Total Number of Microorganisms	Hydrocarbon Utilizers	Microbiological Activity
Organic Carbon	1.000	0.839	0.968	0.656	0.221	0.398
Sediment Accumulation		1.000	0.675	0.961	0.806	0.832
Total Lipids			1.000	0.445	0.459	0.154
Total Number of Microorganisms				1.000	−0.591	0.953
Hydrocarbon Utilizers					1.000	—
Microbiological Activity						1.000

[1]This matrix was derived from a subset of the total data set that included all of the sediment accumulation rate data.

TABLE 2. Interparameter correlation coefficient matrix for the combined lower Cook Inlet and Shelikof Strait Data Sets[1]

	Organic Carbon	Sediment Accumulation	Total Lipids	Total Number of Microorganisms	Hydrocarbon Utilizers	Microbiological Activity
Organic Carbon	1.000	0.294	0.904	0.658	0.222	0.362
Sediment Accumulation		1.000	−0.124	0.356	0.321	−0.249
Total Lipids			1.000	0.429	0.586	0.367
Total Number of Microorganisms				1.000	−0.444	0.802
Hydrocarbon Utilizers					1.000	−0.186
Microbiological Activity						1.000

[1]This matrix was derived from a subset of the total data set that included all of the sediment accumulation rate data.

TABLE 3. Interparameter correlation coefficient matrix for the Norton Sound Data Set[1]

	Organic Carbon	Sediment Accumulation	Total Lipids	Total Number of Microorganisms	Hydrocarbon Utilizers	Microbiological Activity
Organic Carbon	1.000	0.495	0.771	0.277	0.096	−0.051
Sediment Accumulation		1.000	0.725	0.734	0.799	0.756
Total Lipids			1.000	0.653	0.475	0.323
Total Number of Microorganisms				1.000	0.762	0.568
Hydrocarbon Utilizers					1.000	0.918
Microbiological Activity						1.000

[1]This matrix was derived from a subset of the total data set that included all of the sediment accumulation rate data.

of Cook Inlet. Correlation coefficient matrices with the individual data sets are given in Tables 1-3.

There was a significant correlation between rates of sediment accumulation and percent organic carbon in the sediments (Table 1). Kachemak and Kamishak bays are areas of extremely high phytoplankton productivity (Larrance *et al.*, 1977); organic matter produced within the water column of these bays may be deposited within the embayments or swept into and deposited within Shelikof Strait (Feely *et al.*, 1981). Bacterial populations are generally greater in fine-grained sediments than in coarse-grained sediments (ZoBell, 1938); indeed bacterial populations were lower in the coarse-grained central portion of lower Cook Inlet. The hydrocarbons present in Cook Inlet sediments did not appear to exert sufficient selective pressure on the microbial community to lead to large population shifts, resulting in a major enrichment of hydrocarbon-degrading microorganisms in these sediments. There was relatively low overall correlation between concentrations of lipids and concentrations of hydrocarbon-utilizing microorganisms.

With the major exception of Shelikof Strait, areas where there were high rates of sediment accumulation were also areas where the microbial activity was high. The high carbon content in the settling particles undoubtedly acts as a nutrient source for the bacteria and is reflected in higher microbial activities. There are a number of possible explanations for the apparent anomaly in Shelikof Strait. The most likely explanation is related to the fact that the Shelikof Strait sediments are anoxic with a very thin oxidized layer on the surface. This condition is not found in Cook Inlet where the sediments are much less reduced (Massoth *et al.*, 1979). The reduced state of the Shelikof Strait sediments allows the mobilization of certain heavy metals (i.e., Mn, Fe, Cu, Ni, and Co). Morita and Holtum (pers. comm. 1982) have observed that Ni, Cu, Cd, Pb, Zn, and Co at low concentrations significantly reduce the uptake of glucose by marine microorganisms. It is thus possible that the mobilization of heavy metals in Shelikof Strait sediments reported by Appriou (1980) causes the low levels of microbial activity observed in this region.

The highly reduced state of these sediments also suggests that the microbial populations in these sediments are adapted to anaerobic fermentative catabolism. The conditions under which the substrate-uptake studies were conducted were oxidative. The sediment suspensions were essentially saturated with atmospheric oxygen. Under these conditions, obligate anaerobic bacteria would have been inactivated and those organisms that were facultative anaerobes should not be preadapted to efficiently mineralize organic carbon under oxidized conditions.

An alternate explanation is that there is a qualitative difference between the organic material present in the Shelikof Strait and that occurring in Cook Inlet. If one assumes that most of the organic carbon present in Shelikof Strait has been transported from other areas, it is quite likely that it contains proportionately more recalcitrant carbon compounds, such as lignitic material, and less available fixed nitrogen. There is indirect evidence that the level of available, organic, fixed nitrogen might be lower in this area than in Kamishak Bay sediments (Cook Inlet). Haines *et al.* (1981) have reported that in Kamishak Bay sediments, the rate of denitrification is much greater than the rate of nitrogen fixation, indicating that the input of organic fixed nitrogen into these sediments is significant. In the Shelikof Strait sediments, the rates of denitrification and nitrogen fixation are equal, indicating that the system is balanced; that is, the rate at which atmospheric nitrogen is fixed in a form that can be used by microorganisms equals the rate at which microorganisms are returning fixed nitrogen to the atmosphere through denitrification.

The reduced O_2 and fixed nitrogen levels and the elevated levels of some heavy metals have implications relative to potential biodegradation rates of petroleum hydrocarbons in Shelikof Strait sediments. There is extensive documentation showing that crude oil degradation requires both fixed nitrogen and oxygen (Gibbs, 1975; Atlas, 1977). This suggests that if petroleum hydrocarbons were introduced into the sediments of Shelikof Strait, the biodegradation rates would be much lower than they are in the sediments of lower Cook Inlet.

Norton Sound

In the Norton Sound region, sediment originating from the Yukon River appears to move with a cyclonic circulation pattern through the sound. Suspended sediment is transported from the Yukon delta along the periphery of the sound, with 50-60% of the incoming material being deposited in the region northward and eastward of the mouth of the Yukon River. The remaining sediment from the Yukon River appears to be transported to the northwest, through the Bering Strait and into the Chukchi Sea, where it is deposited (Nelson and Creager, 1977).

The alkanes in the sediments of Norton Sound are of biogenic origin, consisting of a mixed input from marine and terrestrial sources. Sediments from the Yukon prodelta are enriched in hydrocarbons relative to other areas in the region investigated. Sediments near the Bering Strait, north of Norton Sound (see Fig. 10) seem to be impoverished in hydrocarbons, possibly because this is not an area of accumulation of fine-grained sediments (McManus *et al.*, 1977). The polynuclear aromatic hydrocarbons in Norton Sound surficial sediments appear to be of pyrolytic origin.

The area around the reported gas seepage in Norton Sound shows no characteristic *n*-alkane or triterpenoidal distributions, both of which are indicative of petroleum. The microbial hydrocarbon utilizer studies and hydrocarbon inhibition studies also indicate a minimal hydrocarbon presence in sediments in the vicinity of the gas seepage. Our results support the findings reported by Kvenvolden *et al.* (1979) that the Norton Sound gas seepage is composed primarily of CO_2.

The distribution of organic carbon and lipids in Norton Sound reflects the counterclockwise pattern of deposition and accumulation of Yukon River-derived sediments. The distribution of clay-sized particles as reported by McManus *et al.* (1977) shows that particles in this size range are most abundant in eastern Norton Sound sediments ($>12\%$ by weight). Although these sediments showed a relatively high carbon content, the organics in this sediment should also have been in the form of larger particles. The cyclonic movement of the water moves finer particles towards the eastern end of Norton Sound where they are deposited and form sediments with clay concentrations greater than 16%. The high concentration of total carbon and lipids in the region supports this hypothesis. The high concentration of hydrocarbon-utilizing bacteria observed in the eastern end of the sound also reflects the input of lipids into this area from the Yukon Riber.

The levels of microbial activity, the numbers of colony-forming units, and the numbers of hydrocarbon-utilizing microorganisms observed in the sandy delta region and muddy eastern end of the sound reflect differences in the particle-distribution patterns. When sediment accumulation rates were compared to the number of colony-forming units, numbers of hydrocarbon-utilizing bacteria (MPNs), and relative microbial activity, the correlation coefficients observed were 0.73, 0.80, and 0.76 respectively (Table 3). The observed correlation coefficients suggest that these three microbial variables are a reflection of accumulation rates.

CONCLUSIONS

Most of the fine-grained sediment that enters Cook Inlet is transported out of the inlet and deposited in Shelikof Strait, with secondary areas of sediment accumulation occurring in Kachemak and Kamishak Bays. About half of the suspended matter from the Yukon River is transported cyclonically and deposited within Norton Sound; the remainder of the material is transported to the northwest into the Bering and Chukchi seas. Areas of sediment accumulation have relatively high organic carbon and lipid concentrations, and relatively high microbial activity. Relatively low microbial activities occur within Shelikof Strait and northwest of the Yukon delta. With the exception of one area in upper Cook Inlet, the sediments of both the Cook Inlet and Norton Sound regions appear relatively free from petroleum-derived hydrocarbons; no evidence from either chemical or microbial data was found for transport of hydrocarbons from oil wells in upper Cook Inlet into the embayments of lower Cook Inlet nor into Shelikof Strait; nor was evidence found for the deposition of hydrocarbons from a gas seepage in Norton Sound sediments. The principal benthic area for accumulation of hydrocarbons spilled into Cook Inlet as a result of oil operations appears to be Shelikof Strait. This area has relatively low microbial activities, and hydrocarbon biodegradation may be restricted, which may lead to long residence times for hydrocarbon contaminants and prolonged ecological impact on the benthic community as a result of petroleum pollution in this area.

ACKNOWLEDGEMENTS

This study was supported by the Bureau of Land Management through interagency agreements with the National Oceanic and Atmospheric Administration under which a multi-year program, responding to needs of petroleum development of the Alaskan continental shelf, is managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) Office.

REFERENCES

APPRIOU, P.Y. 1980. Analysedes technologies de dosage des metaux lourds en trace. Final Scientific Report 78/1886. Université de Bretagne Occidentale, Brest, France. 56 p.

ATLAS, R.M. 1977. Stimulated petroleum biodegradation. CRC Critical Review of Microbiology 6:371-386.

______. 1979. Measurement of hydrocarbon biodegradation potentials and enumeration of hydrocarbon utilizing microorganisms using carbon-14 hydrocarbon-spiked crude oil. In: Costerton, J.W. and Colwell, R.R. (eds.). Native Aquatic Bacteria Enumeration, Activity and Ecology. Philadelphia: American Society for Testing Materials. STP 695:196-204.

BOUMA, A.H. and HAMPTON, M.A. 1976. Preliminary report of the surface and shallow subsurface geology of lower Cook Inlet and Kodiak Shelf, Alaska. U.S. Geological Survey Open File Report 76-695.

CLINE, T.D. and HOLMES, M.L. 1977. Submarine seepage of natural gas in Norton Sound, Alaska. Science 198:1149-1153.

COACHMAN, K., AAGAARD, K. and TRIPP, R.B. 1975. Bering Strait: The Regional Physical Oceanography. Seattle, WA: University of Washington Press. 172 p.

DALEY, R.J. and HOBBIE, J.E. 1975. Direct counts of aquatic bacteria by a modified epifluorescence technique. Limnology and Oceanography 20:875-882.

FEELY, R.A. and MASSOTH, G.J. 1982. Sources, composition and transport of suspended particulate matter in lower Cook Inlet and northwestern Shelikof Strait, Alaska. NOAA Technical Report ERL 415-PMEL 34. 28 p.

______, PAULSON, A.J., LAMB, M.F. and MARTIN, E.A. 1981. Distribution and elemental composition of suspended matter in Alaskan coastal waters. NOAA Technical Memorandum ERL PMEL-27. 119 p.

FLYNN, W.W. 1968. The determination of low levels of ^{210}Pb in environmental materials. Analytica Chimica Acta 43:221-227.

GATTO, L.W. 1976. Circulation and sediment distribution in Cook Inlet, Alaska. In: Hood, D.E. and Barrell, D.C. (eds.). Assessment of Arctic Marine Environment Selected Types. Occasional Publication #4, University of Alaska, Fairbanks, AK. 205-227.

GIBBS, C.F. 1975. Quantitative studies on marine biodegradation of oil. I. Nutrient limitation at 14°C. Proceedings of the Royal Society (London) 188:61-82.

GRIFFITHS, R.P., HAYASAKA, S.S., McNAMARA, T.M. and MORITA, R.Y. 1977. Comparison between two methods of assaying relative microbial activity in marine environments. Applied and Environmental Microbiology 34:801-805.

HAINES, J.R., ATLAS, R.M., GRIFFITHS, R.P. and MORITA, R.Y. 1981. Denitrification and nitrogen fixation in Alaskan Continental Shelf sediments. Applied and Environmental Microbiology 41:412-421.

HEIN, J.R., BOUMA, A.H., HAMPTON, M.A. and ROSS, C.R. 1979. Clay mineralogy, fine-grained sediment dispersal and inferred current patterns, lower Cook Inlet and Kodiak Shelf, Alaska. Sedimentary Geology 24:291-306.

INMAN, D.L. and NORDSTROM, C.E. 1971. On the tectonic and morphologic classification of coasts. Journal of Geology 79:1-21.

KAPLAN, I.R., VENKATESAN, M.I., RUTH, E. and MEREDITH, D.A. 1980. Characterization of organic matter in sediments from Cook Inlet and Norton Sound. Annual Report to the Outer Continental Shelf Environmental Assessment Program. Boulder, CO: Environmental Research Laboratories, NOAA.

KOLLATUKUDY, P.E. and WALTON, T.J. 1972. The biochemistry of plant cuticular lipids. In: Holman, R. T. (ed.). Progress in the Chemistry of Fats and Lipids. Oxford: Pergamon Press. Vol. 13(3):121-175.

KVENVOLDEN, K.A., WELIKY, K., NELSON, H. and DES MARAIS, D.J. 1979. Submarine seep of carbon dioxide in Norton Sound, Alaska. Science 205:1264-1265.

LARRANCE, J.D., TENNANT, D.A., CHESTER, A.J. and RUFFIO, R.A. 1977. Phytoplankton and primary productivity in the northeast Gulf of Alaska. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Report to the Outer Continental Shelf Environmental Assessment Program. Boulder, CO: ERL, NOAA. Vol. 10:1-136.

MASSOTH, G.J., FEELY, R.A., APPRIOU, P.Y. and LUDWIG, S.J. 1979. Anomalous concentration of particulate manganese in Shelikof Strait: an indicator of sediment seawater exchange processes. EOS Transactions of the American Geophysical Union 60(46):1-852.

McMANUS, D.A., KOLLA, V., HOPKINS, D.M. and NELSON, C.H. 1977. Distribution of Bottom Sediments on the Continental Shelf, Northern Bering Sea. U.S. Geological Survey Professional Publication 759-C:01-031.

MUENCH, R.D. and AHLNÄS, K. 1976. Ice movement and distribution in the Bering Sea from March to June 1974. Journal of Geophysical Research 81:4467-4476.

MUENCH, R.D., MOFJELD, H.O. and CHARNELL, R.L. 1978. Oceanographic conditions in lower Cook Inlet: spring and summer 1973. Journal of Geophysical Research 83:5090-5098.

MUENCH, R.D., TRIPP, R.B. and CLINE, J.D. 1981. Circulation and hydrography of Norton Sound. In: Hood, D.W., and Calder, J.A. (eds.). The Eastern Bering Sea Shelf: Oceanography and Resources. Washington, D.C.: U.S. Department of Commerce. Vol. I:77-94.

NELSON, C.H. and CREAGER, J.S. 1977. Displacement of Yukon-derived sediment from Bering Sea to Chukchi Sea during Holocene time. Geology 5:141-146.

NITTROUER, C.A., STERNBERG, R.W., CARPENTER, R. and BENNETT, J.T. 1979. The use of ^{210}Pb geochronology as a sedimentological tool: application to Washington Continental Shelf. Marine Geology 31:297-316.

ROSENBERG, D.H. and HOOD, D.W. 1967. Descriptive oceanography of Cook Inlet, Alaska. American Geophysical Union Transactions 048(1). 132 p.

ROUBAL, G. and ATLAS, R.M. 1978. Distribution of hydrocarbon-utilizing microorganisms and hydrocarbon biodegradation potentials in Alaskan Continental Shelf areas. Applied and Environmental Microbiology 35:897-905.

SHARMA, G.D. 1974. Contemporary depositional environment of the eastern Bering Sea. In: Hood, D.W. and Kelley, E.J. (eds.). Oceanography of the Bering Sea. University of Alaska, Institute of Marine Science Occasional Publication Number 2. 517-552.

______. 1979. The Alaskan Shelf: Hydrographic, Sedimentary and Geochemical Environment. New York: Springer Verlag. 498 p.

VENKATESAN, M.I., SANDSTROM, M., BRENNER, S., RUTH, E., BONILLA, J., KAPLAN, I.R. and REED, W.E. 1981. Organic geochemistry of surficial sediments from the eastern Bering Sea. In: Hood, D.W. and Calder, J.A. (eds.). The Eastern Bering Sea Shelf: Oceanography and Resources. Washington, D.C.: U.S. Department of Commerce. 389-409.

ZOBELL, C.E. 1938. Studies on the bacterial flora of marine bottom sediments. Journal of Sedimentary Petrology 8:10-18.